Bipolar-Hyper-Shell Galactic Center Statrburst Model: Further Evidence from ROSAT Data and New Radio and X-ray Simulations

Yoshiaki SOFUE
Institute of Astronomy, University of Tokyo, Mitaka, Tokyo 181-8588
E-mail: sofue@ioa.s.u-tokyo.ac.jp

ABSTRACT

Using the all-sky ROSAT soft X-ray and 408-MHz radio continuum data, we show that the North Polar Spur and its western and southern counter-spurs draw a giant dumbbell-shape necked at the galactic plane. We interpret these features as due to a shock front originating from a starburst 15 million years ago with a total energy of the order of $\sim 10^{56}$ ergs or 10^5 type II supernovae. We simulate all-sky distributions of radio continuum and soft X-ray intensities based on the bipolar-hyper-shell galactic center starburst model. The simulations can well reproduce the radio NPS and related spurs, as well as radio spurs in the tangential directions of spiral arms. Simulated X-ray maps in 0.25, 0.75 and 1.5 keV bands reproduce the ROSAT X-ray NPS, its western and southern counter-spurs, and the absorption layer along the galactic plane. We propose to use the ROSAT all-sky maps to probe the physics of gas in the halo-intergalactic interface, and to directly date and measure the energy of a recent Galactic Center starburst.

1. Introduction

A bipolar hyper-shell model has been proposed for the North Polar Spur (NPS) (Sofue 1977), in which the NPS and its western and southern counter-spurs are interpreted as due to a dumbbell-shaped shock front induced by a giant explosive event at the Galactic Center. Such an impulsive energy input may have been originated by a starburst 15 million years ago (Sofue 1984, 1994). An alternative mechanism to cause such giant shells in the halo would be a single energetic explosion at the Galactic nucleus (Oort 1977). Giant shell structures could also be produced by a stellar-wind driven coherent galactic wind (e.g., Heckman et al 1990). Since the cooling time in the halo is much longer than the shell's life time, any of these mechanisms will, however, result in a similar shocked shells in the halo, given the same amount of total energy. Another alternative, traditional idea to explain the NPS is the local-shell hypothesis, in which the NPS is interpreted as due to a very unique supernovae remnant of the largest diameter in the Galaxy (Berkhuijsen et al. 1971; Egger 1993; Egger and Aschenbach 1995; and the literature cited therein).

The propagation of a shock front in the galactic halo can be simulated by applying a shock-tracing method developed by Sakashita (1971) and Möllenhoff (1976) to a case of point explosion at a center of a disk surrounded by a halo and intergalactic uniform gas (Sofue 1984). The galactic-center explosion hypothesis tries to explain the NPS as well as the other spurs surrounding the galactic center region by a single Galactic event, based not only on the morphology but also on a distance estimate of NPS from soft-X ray extinction (Sofue 1994).

In the present paper, we revisit the galactic-center explosion hypothesis. We will extend the arguments given in Sofue (1994), which were based on the Winsconsin X-ray experiments data (McCammon et al 1983; McCammon and Sanders 1990). We will discuss the origin of the NPS and related galactic spurs using the 408-MHz all-sky radio data (Haslam et al 1982) and the ROSAT X-ray images (Snowden et al 1997). We simulate X-ray all-sky views based on the BHS (bipolar hyper-shell) model in order to morphologically reproduce the ROSAT all-sky views at various energy bands. We also discuss the implication of the bipolar hyper shell in dating and measuring the recent Galactic starburst. We further propose to use the ROSAT all-sky data to probe the physics of gas in the galactic halo and intergalactic space of the Local Group.

2. All Sky Radio and X-ray Data

2.1. All-sky views

In Fig. 1 we compare the radio and X-ray views of the whole sky in the (l, b) coordinates in Aitoff diagrams. Fig. 1a shows an enhanced view of galactic radio spurs obtained by applying a relieving technique (Sofue 1993) to the 408 MHz all-sky map (Haslam et al. 1982). Fig. 1b is the ROSAT all-sky map in the R45 ($\sim$0.75 keV) band as reproduced from Snowden et al (1997). These figures demonstrates that the major galactic spurs both in radio and X-rays are found in the central $100^\circ (\pm 50^\circ)$ region around the Galactic Center. The North Polar Spur (NPS) and its western and southern counterparts compose giant Ω shapes, drawing a dumbbell shape centered on the Galactic Center and necked at the galactic plane.

— Fig. 1 —

2.2. Radio spurs

Fig. 2 shows a radio view in a 100° squared region around the Galactic Center. Here, a relieving method to enhance the spurs has been applied in the direction of longitude (left panel) and in the radial direction (right panel). The NPS comprises a well-defined radio arc anchored to the galactic plane at $l \sim \pm 20^\circ$, and draws a giant arc toward the North Galactic Pole. The radio brightness along the NPS increases toward the galactic plane, attaining a maximum at $(l, b) \sim (20^\circ, 0^\circ)$. The width of the spur (half-intensity length across) decreases toward the galactic plane, and therefore, the NPS ridge becomes sharper toward the galactic plane (Sofue and Reich 1979).

— Fig. 2 —

The NPS draws a giant loop toward high latitudes, and returns to the galactic plane where it merges with a spur emerging from the galactic plane at $l \sim 340^\circ$. We call this western spur NPS-West. A western half of Loop IV, which is highly asymmetric and lacks the eastern half, makes a part of NPS-West. The NPS and NPS-West, thus, compose a giant Ω shape in the halo above the Galactic Center, with its axis roughly coinciding with the galactic rotation axis at $l = 0^\circ$. A southern counterpart of the NPS is visible at $l \sim 20^\circ$, extending from $(l, b) \sim (20, 0)$ toward $(30, -30$, which we call the South Polar Spur (SPS). Also, a western

counterpart of SPS is found at $(l, b) \sim (340, 0)$ to $(320, -30)$, which we call SPS-West.

These four spurs, NPS, NPS-West, SPS, and SPS-West, are the most prominent features among the numerous galactic radio spurs. These four spurs compose a huge dumbbell-shape necked at the galactic plane and are about symmetric with respect to the Galactic Center. We comment that Loop I, which has been defined as a complete loop of diameter 120°centered on $(l, b) = (330°, 30°)$, is hard to trace in the present enhanced images (Fig. 1, 2).

2.3. X-ray Spurs

As shown in Fig. 1b, the R45-band (0.75 keV) X-ray intensity at $b > 10°$ has a global enhancement around the Galactic Center, which is due to the high-temperature gas in the galactic bulge (McCammon et al 1983). Snowden et al (1997) have further noticed cylindrical features in the R45 and R67 (1.5 keV) band maps, which emerge from the central galactic disk toward the halo. They also attribute these features to high-temperature gas around the galactic center. This fact indicates that the local HI disk is transparent at $b >\sim 10°$ for X-rays at ≥ 0.75 keV.

A giant shell structure of the NPS is clearly visible in the R45 and R67 bands. In Fig. 3 we compare the radio and R45-band images of the NPS. The western end of the X-ray NPS also returns to the galactic plane at $l \sim 340°$ (NPS-West), and draws a giant Ω together with the NPS. Southern counterparts to these features are also visible. Particularly, the SPS-West is clearly recognized in X-rays: an R45-band spur emerges from $l \sim 340°$ toward the southern galactic pole, which is symmetric to the NPS about the Galactic Center. The SPS is also visible at $l \sim +30°$, though fainter in R45-band, while it is more clearly visible in an R45/R67-ratio map. These northern and southern X-ray spurs are associated with the radio spurs (NPS, NPS-West, SPS, and SPS-West), and draw a dumbbell-shape necked at the galactic plane. We may, hence, interpret that Snowden et al.'s "cylinder" would comprise the NPS, NPS-West, SPS and SPS-West.

— Fig. 3 —

The R12-band (0.25 keV) X-ray emission from the NPS is strongly absorbed below $b = 60°$, and is hardly visible below 30° (Snowden et al 1997). The NPS shows up most clearly in the R45-band (0.75 keV), while the emission is significantly absorbed in the galactic disk at $b < 10°$. R67-band (1.5 keV) X-rays are also strongly absorbed near the galactic plane, indicating that the X-rays from the NPS originates in the space further than the HI disk (Sofue 1994). Moreover, the X-rays become harder toward the galactic plane, as indicated by the clear decrease in the R45 to R67 intensity ratio toward the galactic plane. By comparing the R45 and R12-band intensities, we have shown that the HI mass toward $b = 30°$ to be 7×10^{20} H cm^{-2}, which is greater than the observed value (5×10^{20} H cm^{-3}). Sofue (1994) has thus shown that the X-rays at $b \sim 30°$ originate *beyond* the hydrogen layer, and the distance is greater than 0.6 kpc. Namely, the NPS is an object which is located in the galactic halo. The distance to the NPS has been subject to debates. We now know that it is beyond 0.6 kpc, which would allow us two possible interpretations: One possibility is that the NPS is a local object at ~ 1 kpc, originating from supernova explosions at high altitude out of the galactic plane. Another possibility is that it is a Galactic-scale object related to the Galactic Center activity.

3. Comparison of Bipolar Hyper-Shell Model with Data

3.1. BHS Model

We interpret the observed radio and X-ray features in terms of the galactic-center explosion hypothesis. Our idea is based on the symmetric appearance of the radio and X-ray shells with respect to the galactic plane and the Galactic Center, which compose a huge dumbbell shape apparently centered on the Galactic Center (GC). We, here, assume that the center of the dumbbell coincides with the GC, and take the distance to the GC to be 8 kpc. Then, the radius of each shell is several kpc. Our idea is also based on the fact that many spiral galaxies exhibit galactic-scale outflows in the forms of dumbbell-shaped shocks, bipolar cylinders, and galactic-scale jets, and we consider that the Milky Way Galaxy would have experienced similar phenomena.

NGC 253 exhibits a dumbbell-shaped shells in X-rays above and below the galactic plane, each about 5 kpc diameter (Vogler and Pietsch 1999a; Pietsch et al 1999) , which would be a result of a starburst and related outflow (Heckmann et al. 1990). NGC 3079 exhibits a pair of radio continuum shells in the halo in both sides of the nucleus, each about 3 kpc diameter, which is considered to be an ejection from the

central activity (Duric et al 1983). It also exhibits an Hα cone-shaped shell of radius about 1 kpc, coaxial to the radio shells, most likely induced by an outburst from the nuclear region (Cecil 1999). M82 is a starburst galaxy, which ejects a galactic-scale flow through bipolar cylindrical jets (Nakai et al 1987). We emphasize that all these out-of-plane features, including the hyper shell in the Milky Way, require a similar amount of total energy input in the central regions of the galaxies, which is of the order of 10^{55} to 10^{56} ergs (e.g. Pietsch et al 1999), or equivalent to 10^4 to 10^5 type II supernovae.

3.2. Adiabatic-Shock Envelope Method

The propagation of a shock wave through the galactic halo induced by a point energy injection at a galactic center can be calculated by applying the shock envelope-tracing method of Sakashita (1971) and Möllenhoff. They have extended the Laumbach and Probstein's (1969) method for tracing the evolution of a shock front to a case of axi-symmetric distributions of ambient gas. The flow field is assumed to be locally radial, and the gas is adiabatic, and, therefore, the heat transfer by radiation and counter pressure are neglected. The density contrast between the shock front and ambient gas is given by $(\gamma+1)/(\gamma-1) = 4$ for $\gamma = 5/3$, where γ is the adiabatic exponent of the gas. For a typical density of 10^{-3} H cm^{-3} and temperature of 10^7 K for the shock-heated halo gas, the cooling time due to the free-free thermal emission is approximately 5×10^8 years. Hence, the assumption of adiabatic gas is valid in our calculation, in which the shell's life time is estimated to be of the order of 10^7 years, as shown below.

The equation of motion of the shock wave is given by (Möllenhoff 1976):

$$E = \int_0^R \frac{P}{\gamma-1} 4\pi r^2 dr + \int_0^R \frac{1}{2}\left(\frac{\partial r}{\partial t}\right)^2 \rho_0 4\pi r_0^2 dr_0.$$

Here, E is the total energy of the explosion, P is the internal pressure, γ is the adiabatic exponent, which is assumed to be 5/3 hereafter, ρ_0 is the unperturbed ambient gas density, r is the radius from the explosion center, with suffix 0 denoting the quantities of the unperturbed ambient gas, and R is the radius of the shock front. Assuming that the snow-plowed mass is strongly concentrated near the front, the above equation leads to equation to express the shock radius R as follows (Sakashita 1971; Möllenhoff 1976):

$$E = \frac{1}{3(\gamma+1)^2} \times$$

$$\left[\frac{4(2\gamma-1)}{(\gamma-1)} JR\ddot{R} + \left(\left\{2IR + \frac{8\gamma}{(\gamma+1)} + 3\right\} J + \frac{2M(\gamma+1)}{(\gamma-1)}\right) \dot{R}^2\right].$$

Here,

$$I = \left[\frac{4\pi}{r_0}\frac{d\rho_0}{dr_0}\right]_R,$$

$$J = \int_0^R \rho_0 4\pi r_0^2 dr_0,$$

and

$$M = \rho_0 \frac{4\pi}{3} R^3.$$

The unperturbed density distribution of gas is assumed to comprise a stratified disk, a halo with an exponentially decreasing density, and intergalactic gas with uniform density. The hydrogen density in the galactic plane is taken to be 1 H cm^{-3} in the solar vicinity. The gas distribution is approximated by the following expression.

$$\rho_0 = \rho_1 \exp(-z/z_1) + \rho_2 \exp(-z/z_2) + \rho_3.$$

Here, suffices 1, 2 and 3 denote quantities for the disk, halo and intergalactic gas, respectively, ρ is the density, z is the height from the galactic plane, z_i is the scale thickness of the disk and halo. Here, ρ_1, ρ_2, and ρ_3 are ~ 1, 0.01, and 10^{-5} H cm^{-1}, and z_1 and z_2 are ~ 0.1 and 1 kpc, respectively.

This model has been applied to the Galactic Center in order to fit the North Polar Spur (Sofue 1984, 1994). The dumbbell-shaped shell structure and the NPS are well reproduced by a case in which the explosion energy is $E = 3 \times 10^{56}$ erg. Fig. 4 shows a calculated shock front at $t = 10$ and 20 Myr as reproduced from Sofue (1984). In this model, the expansion velocity of the shock front amounts to several hundred km s^{-1} and the gas is heated up to 10^7 K, emitting soft X rays observable in the ROSAT energy bands at ~ 0.25, 0.75 and 1.5 keV.

Numerical simulations of smaller-scale outflows from the galactic plane have been obtained in hydrodynamic scheme (e.g., Tomisaka and Ikeuchi 1986) and in MHD (magneto-hydrodynamic) treatment (e.g., Uchida et al 1985). However, these simulations have been obtained only for smaller scale outflows with scales less than one kpc, so that they cannot be applied to the present case with a much larger-scale

shells expanding from the upper halo to the intergalactic space.

— Fig. 4 —

3.3. Radio and X-ray Simulations

3.3.1. Radio Sky

We simulate radio and X-ray intensity distributions on the sky based on the bipolar hyper-shell model. In order to simulate the radio and X-ray emissivity in the bipolar-hyper shells, as calculated above, we approximate the shape of each half of the dumbbell-shaped shock by an ellipse. Here, we calculate a case for a shell whose center is at $z = \pm 6$ kpc and the radii 6 and 9 kpc in the radial and vertical (z) directions, respectively. The volume emissivity of synchrotron radiation is calculated from the density contrast of the shocked gas, in which magnetic fields and cosmic-ray electrons are considered to be compressed adiabatically with shock-compression of the halo gas, and the volume emissivity of synchrotron radio radiation is assumed to be proportional to $(\rho/\rho_0)^\beta$ with β being approximately 4, where ρ and ρ_0 are gas densities in the shocked shell and unperturbed halo gas, respectively. In the present simulation, the profile of radio emissivity perpendicular to the shell surface is simply represented by an exponentially decreasing function behind the shock front toward the center with a scale thickness of 500 pc (Fig. 4). The emissivity also decreases with the height from the galactic plane with a scale height of 3 kpc, corresponding to exponentially decreasing density of the halo gas.

In addition to the hyper shell, we assume the existence of a galactic disk of scale height of 0.5 kpc and scale radius of 6 kpc, which is further embedded in a fatter disk with 3 and 8 kpc scale height and radius, respectively. The emissivity is, therefore, assumed to have the form expressed by

$$\epsilon = \epsilon_{\rm s} + \epsilon_1 + \epsilon_2 = \epsilon_{\rm s} + \epsilon_0 \Sigma_{i=1}^{2} {\rm exp}(-r/r_i - z/z_i),$$

where $\epsilon_{\rm s}$ is the emissivity in the shell as described above (Fig. 4), ϵ_0 is a constant, ϵ_1 and ϵ_2 represents the disk and fat components, respectively, $r_1 = 6$ kpc, $z_1 = 0.5$ kpc, $r_2 = 8$ kpc, and $z_2 = 3$ kpc. No extinction in the radio band is assumed throughout the galactic disk and halo. In Fig. 5a we show the radio continuum result, and compare with the observed 408 MHz all-sky map (Fig. 5c). The global radio distribution is well reproduced by the model, and the NPS is reproduced as a radio ridge emanating from the galactic disk.

— Fig. 5 —

3.3.2. Radio Sky with Spiral Arms

We further simulate a case in which the disk component comprises logarithmic spiral arms, as illustrated in Fig. 6. The radio continuum emissivity is assumed to have a form

$$\epsilon_1 = \epsilon_0 {\rm exp}(-r/r_1 - z/z_1){\rm cos}(\theta - \eta log(r/r_0))^k.$$

Here, θ is the galacto-centric azimuthal angle, η is the inverse of the pitch angle of spiral arms, $\eta = 1/tan\ p$ with $p = 6°$, $\alpha = 5.1$ is a correction factor to fix the total luminosity to be the same as that when no spiral arms are assumed, and $k = 16$ is introduced to mimic a narrow condensation of the emissivity in the arms. The simulated result is shown in Fig. 5b. In addition to the spurs due to the hyper shells as in Fig. 5a, there appear many spurs extending toward high latitudes in both sides of the galactic plane. These spurs are tangential views of bank-shaped spiral arms which are extending into the halo. It is interesting to note that the tangential directions of the local spiral arms coincide with the western half of Loop I, Loop II and III, which was already pointed out earlier (Sofue 1976). Simulated inner-arm spurs are also found to reproduce many observed inner radio spurs, while their exact positional coincidence is out of the present simplified spiral arm model.

— Fig. 6 —

3.3.3. X-ray Sky

X-ray emission from the hyper shells is assumed to be thermal free-free radiation, whose emissivity is given by

$$\epsilon = n_{\rm e}^2 \Lambda \propto \rho^2 T^{1/2}.$$

Here, Λ is the cooling function of the gas. Since the temperature is as high as $T \sim 10^7$ K in our simulation, the radiation is almost totally free-free, and the contribution by recombination lines from hydrogen, helium, and metals, which are significant at $T \sim 10^4 - 10^6$ K, are not significant. For a typical density and temperature of about 10^{-3} H cm^{-3} and 10^7 K, respectively, the value of Λ is 10^{-21} erg cm^{-9} s^{-1}, and the emissivity is approximately 10^{-27} erg cm^{-3} s^{-1}. A typical emission measure along the hyper shell ridge is $n_{\rm e}^2 L \sim 10^{-2}$ cm^{-6}pc for a tangential

pass in the shell of about 2 kpc. For simplicity, we assume that the temperature of X-ray emitting gas is constant in the shocked shell. The assumption of constant temperature may not be a good approximation for lower latitude regions, where the propagation velocity is lower than that of the upper part, and, therefore, the temperature is lower. However, the low-latitude regions are strongly absorbed by the HI gas layer, and such temperature gradient in the shell would not much improve the accuracy of the present simulation.

In addition to the hyper shells, we assume a galactic ridge X-ray component of scale height of 500 pc, and a bulge component of scale radius 1 kpc. Emission from ambient halo gas is neglected, because the temperature and density will not be sufficiently high to emit X-rays in the present energy bands.

The X-ray intensity, I, is calculated by a transfer equation given by

$$dI = \epsilon_{\rm X} ds - \kappa I ds,$$

where the first term in the right-hand side is the emission measure with $\epsilon_{\rm X}$ being the X-ray emissivity, and the second term represents the absorption rate with κ being absorption coefficient, and s is the distance along the line-of-sight.

The interstellar extinction of soft X rays occurs due to photoelectric absorption by metals, and has been calculated for the solar metal abundance by Morrison and McCammon (1983). The energy dependence of the cross section per H atoms can be approximated by $\sigma \propto E^{-2.5}$ (Ryter 1996) in the present energy bands, where E is the photon energy of X rays. The absorption coefficient κ is, then, approximately represented by

$$\kappa = (n_{\rm H}/N_{\rm H}^0)(E/E_0)^{-2.5},$$

where $n_{\rm H}$ is the number density of hydrogen atoms, and $N_{\rm H}^0$ is the e-folding column density of interstellar neutral hydrogen at the photon energy E_0. At $E_0 = 0.75$ keV, the cross section is $\sigma = 4 \times 10^{-22}$ cm^2 per H atom, which yields an e-folding column density of 2.5×10^{21} H atoms. According to the transmission diagram of Snowden et al (1997), the e-folding column density for R45 band X-rays ($E_0 = 0.75$ keV) is also read as $N_{\rm H}^0 = 3 \times 10^{21}$ H cm^{-2}. We adopt this value for the R45 band (0.75 keV). However, the ROSAT energy bands are rather broad, containing significantly higher and lower energies around the representative energies. In our simulation, therefore, we adopt three representative cross sections at R12, R45 and R67 bands, which are 10, 1 and 0.1 times the value at 0.75 keV, respectively.

The neutral hydrogen layer is assumed to have a density distribution expressed by

$$n_{\rm H} = n_0 {\rm exp}(-r/r_{\rm H} - z/z_{\rm H}),$$

where n_0 is the mean density in the solar vicinity, and is taken to be $n_0 = 1$ H cm^{-3}, $r_{\rm H} = 8$ kpc is the scale radius of the gas disk, and $z_{\rm H} = 100$ pc is the scale height.

Fig. 7a shows the calculated intrinsic intensity distribution, where no galactic absorption is taken into account. Fig. 7b is a result calculated for R45-band X-rays, which suffer from absorption by the galactic atomic hydrogen layer. The observed absorption features near the galactic plane is well reproduced by this model. The hyper shells are observed as a set of double-horn features extending toward the galactic poles, composing dumbbell-shaped ridges, and mimic the observed X-ray spurs (NPS, NPS-West, SPS and SPS-West). Fig. 7c shows a case in which the hyper shells are replaced by bipolar parabolic cones, which are open toward the polar axes as illustrated in Fig. 4c. The conical cylinder model appears, however, worse in order to reproduce the observed round shape of the North Polar Spur in radio and X-rays. In both cases of hyper shells and conical cylinders, the observed cylindrical spurs at lower latitudes in X-rays (Snowden et al 1997) are well reproduced. The bulge component is also visible in the models, as the two enhanced regions above and below the galactic center.

— Fig. 7 —

3.3.4. X-ray Sky with Spiral Arms

Fig. 8b shows results for a case in which the absorbing hydrogen gas is assumed to be condensed in logarithmic spiral arms of pitch angle 6° and the arm width is taken to be 1/5 of the arm separation, as illustrated in Fig. 6. Hence, the peak hydrogen density in the local arm is about 5 H cm^{-3}. The hydrogen density distribution is expressed by

$$n_{\rm H} = \alpha n_0 {\rm exp}(-r/r_H - z/z_H) {\rm cos}^k(\theta - \eta {\rm log}\ r/r_0).$$

Here, θ and η have the same meaning as above. Since the tangential directions of the spiral arms are asymmetric around the galactic center, the absorption feature near to the galactic plane is also asymmetric.

In order to examine how the X-ray sky looks like in different energy bands, we have performed simulations for different values of the absorption coefficient. Fig. 8 shows the calculated results for three different κ values: (a) ten times the above value, (b) as above, and (c) one tenth. Fig. 8a, b, and c, therefore, roughly correspond to X-ray views in the R12, R45, and R67 bands, respectively. In Fig. 8, we compare the simulated results with the corresponding ROSAT images.

The R12-band model is characterized by a wide absorption lane along the galactic plane, where X-rays from the galactic plane and bulge are almost totally absorbed. The hyper shells also suffer from strong absorption, while high-latitude parts are still visible as the northern and southern "polar-caps", which are indeed observed in the ROSAT R12-band image. We also obtain a good reproduction of the observed ROSAT X-ray features in R45 and R67 bands, as discussed in the previous subsections.

3.4. Summary of Comparisons Between Models and Data

We have revisited the hyper-shell model of radio and X-ray spurs around the Galactic Center, and simulated the all-sky view of radio and X-ray emissions. The model can mimic the observed all-sky views fairly well in radio (Haslam et al 1982) and ROSAT X-rays (Snowden et al 1997), as shown in Fig. 5, 7 and 8. The simulation could reproduce the following characteristic properties for the galactic spurs :

(1) The major spurs in the whole sky are found around the Galactic Center at $330° < l < 30°$ (NPS, NPS-West, SPS, and SPS-West).

(2) These four spurs are located apparently symmetric with respect to the rotation axis of the Galaxy as well as to the galactic plane.

(3) Southern X-ray spurs exhibit cylindrical appearance.

(4) X-ray spurs in R45 (0.75 keV)- and R67 (1.5 keV) bands exhibit a sharp absorption lane along the galactic plane.

(5) R12-band (0.25 keV) spurs comprise northern and southern polar caps at high latitudes, $b >\sim 30 - 40°$, while lower-latitude emission is hardly visible due to broad and strong absorption lane in the local galactic plane.

(6) An X-ray bulge is visible above and below the Galactic Center in R45 and R67 bands.

(7) Besides the BHS-related spurs, a more number of radio continuum spurs are observed in the tangential directions of the inner and local spiral arms, with the most prominent spiral-arm spurs emerging at $l \sim 80°$ and $l \sim 260°$ corresponding to the local arm.

4. Discussion

4.1. Starburst Origin of Bipolar Hyper Shells

4.1.1. Time Scale and Energetics

In our model, the energy injection at the Galactic Center has been assumed to be impulsive, and the shock is strong enough to create a well-defined shell structure. The time scale of the explosive event at the Galactic Center is assumed to be sufficiently shorter than the expanding time scale of the hyper shell. Since the expanding time scale is of the order of $t \sim r/v \sim 10^7$ years for r ~several kpc and v ~300 km s^{-1}, the explosion time scale should be shorter than a few million years. The required total energy given to the interstellar gas is of the order of $10^{55} - 10^{56}$ ergs in order to heat the gas up to $\sim 10^7$ K at the BHS front. Such impulsiveness and robustness of the energy release can be explained if the Galactic Center has experienced a starburst about 15 million years ago, lasting for a few million years or shorter, during which $\sim 10^5$ type II supernovae exploded. If this starburst model is correct, the ROSAT all-sky data can be used to directly date and measure the energy of the recent starburst in our Galaxy.

4.1.2. Hyper Shell's Neck in the Disk and the 2.4-kpc Expanding Ring

By an MHD wave approximation of a blast wave from the Galactic Center we have shown that a significant fraction of low-latitude front focuses on the galactic plane, with the gas-flow paths being diffracted due to velocity gradient, which leads to an expanding gaseous ring in the disk (Sofue 1977). The tangential directions of this expanding ring in the present model, which coincide with the BHS dumbbell's neck, are at $l \sim \pm 20°$. In fact, the root of the observed radio NPS crosses the galactic plane also at $l \sim \pm 20°$ (Sofue and Reich 1979). It is interesting to point out that there is an expanding feature in the HI line emission in coincidence with this tangential direction of the hyper shell, known as the "3 kpc (2.4 kpc) expanding ring" of HI gas (Oort 1977). Since the expanding velocity of the hyper shell in the disk re-

gion is significantly decelerated, the ring will not not be heated up to emit X rays, and, therefore, the ring may not be detectable in X-rays at this low latitude.

The Milky Way is also known to have another gaseous ring in the disk, the "4-kpc molecular ring", with high density concentration of molecular and HI gases. Although there is a suggestion about its origin as due to a resonance in a barred potential (Nakai 1992), it may also be possible to explain such a larger-radius ring by focusing of an older expanding blast wave induced by an earlier starburst recurrently occurring in the Galactic Center.

4.2. Alternative Interpretations

4.2.1. Alternative Impulsive Energy Injections at the Galactic Center

We may consider some alternative mechanisms to cause an impulsive energy release in the Galactic Center region. One possibility is a single gigantic explosion at the Galactic nucleus (Oort 1977), possibly caused by an infall of a star or its debris into the central massive black hole (Genzel et al 1997; Ghez et al 1998). A stellar-wind driven Galactic wind (Heckman et al 1990) could also produce a shell structure, as observed with ROSAT for NGC 253 (Pietsch et al 1999). However, if the wind is steady and longer-lived than 15 million years, the flow would have become already open-cone shaped, which does not appear to fit the observations. Another possible mechanism is a "meteorite-like impact" by infalling gas clouds from intergalactic space onto the galactic gas disk, such as debris of the Magellanic Clouds after three-body dynamical interaction of the galaxies and the Clouds. If several giant molecular clouds hit the gas disk at about the escaping velocity, ~ 400 km s^{-1}, and the kinetic energy is converted into heat, the impact will be equivalent to an explosion of energy of $\sim 10^{55}$ ergs.

Since the cooling time of the hyper shell, which is of the order of 10^9 years, is much longer than the expansion time scale, any of these mechanisms will result in a similar shocked shells in the halo, if the total input energy is approximately the same.

4.2.2. On the Local-Shell Hypothesis

Although we have proposed a unified model to explain the galactic spurs in terms of a single event at the Galactic Center, we cannot exclude the possibility that local objects such as nearby supernova remnants are superposed (Snowden et al 1997). If we stand on the local-shell model, the sharp absorption lane along the galactic plane in R45 and R67 bands must be explained by an intrinsic depression of intensity below $l \sim 10 - 20°$. We have in fact simulated intensity distributions in soft X-ray bands as expected from a local uniform shell of diameter 300 pc at a distance of 200 pc embedded in a hydrogen layer of a scale height 100 pc and local density 1 H cm^{-3}. In R45 and R67 bands, no sharp absorption feature at $l < 10 - 20°$ was obtained by the simulation because of the negligible extinction for its proximity. The absorption feature can be reproduced, only if the shell is not a unique emission source, but it is superposed by a more distant emission such as from the Galactic bulge (Snowden et al 1997). In R12 band, the local-shell model could mimic the observation, similarly to the hyper-shell model, because the distance does not affect the simulated results, since the absorption feature is produced very locally: Regardless its distance, half the shell at high latitudes is visible in R12 band, while the lower half at $b <\sim 30°$ is absorbed by the local hydrogen layer.

A traditional idea to explain the NPS is the local supernova hypothesis, which attributes the spur to a nearby shell of supernova remnant(s) of the largest diameter in the Galaxy, called Loop I (e.g., Berkhuijsen et al 1971; Egger and Aschenbach 1995). The shell is the oldest supernovae remnant, and therefore, the probability to detect similar objects, if there exist any in the Galaxy, is much higher than that to find usual supernova remnants, almost two hundred of which are already discovered. Since the NPS is sufficiently bright in synchrotron radio emission, with the typical brightness bing ~ 50 K at 408 MHz, and is apparantely very large, such shells should have been easily detected, if it existed anywhere in the Galaxy. In this sense, the NPS is a very unique (peculiar) object, if we stand on the local supernova hypothesis. Note that Loops II and III, whose brightness temperatures are at most about 4 K at 408 MHz, are an order of magnitude less luminous than NPS. Note also that the major parts of Loops II and III can be explained by local arm spurs in the present model (Fig. 5; see also Sofue 1976).

4.3. Implications of the BHS Model as a Probe of Halo and Intergalactic Gas Dynamics

4.3.1. Halo-Intergalactic Interface

If the bipolar-hyper shell model applies, the all-sky ROSAT X-ray and radio data can be used not only to measure the starburst, but also to probe the physics such as the density distribution and magnetic fields in the galactic halo as well as those in the interface from the halo to intergalactic space. The morphology of the hyper shell is sensitive to the density distribution in the halo, and particularly, the shell shape in the uppermost part manifests the halo-intergalactic density structure (Sofue 1984). If the intergalactic gas density is very low, the shell will become more open and conical, while if it is higher, the shell becomes more compact and round. The shell morphology, and therefore the density structure, is also dependent on the expanding velocity, which is directly related to the gaseous temperature inferred from soft X-ray spectra. More detailed hydrodynamical simulations with quantitative and morphological fitting to the ROSAT data would provide us with much advanced knowledge about the galactic halo and intergalactic space in the Local Group.

4.3.2. Asymmetry of the Hyper Shell

The observed NPS and its southern counter spurs are asymmetric in morphology and intensities with respect to the galactic plane as well as to the rotation axis of the Galaxy. Such asymmetry can be attributed to anisotropy in the halo and intergalactic space. Intergalactic wind, or equivalently, motion of the Galaxy in the Local Group, may also cause an asymmetry of the hyper shell. Hence, the morphological appearance of the hyper shell may be also used to probe the anisotropy and winds in the halo and intergalactic space.

We have not taken into account the local fluctuation of hydrogen gas and molecular clouds, which also cause asymmetry in the X-ray absorption appearance. In fact the galactic layer is full of clouds, HI spurs, shells, and holes (Hartmann and Burton 1997). The Hydra spur of HI gas is a dense, leaned spur emanating from the galactic disk at $l \sim 20^\circ$ toward $(l, b) \sim (0^\circ, 30^\circ)$, crossing the NPS root nearly perpendicularly, which would affect the absorption feature of the NPS. A more sophisticated modeling of the X-ray views and detailed comparison with the ROSAT survey is subject for future simulations.

4.4. Implications of the BHS Model for large-scale Structure in Nearby Galaxies

As described in Section 3.1, many spiral galaxies exhibit similar hyper shells in their halos (Sofue 1984): NGC 253' dumbbell-shaped shells (Vogler and Pietsch 1999a; Pietsch et al 1999), NGC 3079's shells in radio continuum, Hα and X-rays (Duric et al 1983; Pietsch et al 1998; Cecil 1999). M82's bipolar cylindrical jets (Nakai et al 1987). NGC 4258's anomalous arms could also be due to some out-of-plane partial shells (van ALbada and van der Hulst 1982; Vogler and Pietsch 1999b). We stress that these out-of-plane features, including our hyper shell in the Milky Way, require a similar amount of total energy of the order of 10^{55-56}, or 10^4 to 10^5 type II supernovae. This fact suggest that the BHS starburst model would be more general to model the extragalactic cases. Simulations of ROSAT X-ray features in these objects based on our model, which is in preparation, would provide us with a clue to date and measure the responsible explosive events at their centers, such as their starburst history as well as information about the gas dynamics in their halo-intergalactic interface. Such simulations would also give a clue to compare the halo-intergalactic gas physic and starbursts in external galaxies with those in our Milky Way.

5. Summary

We have revisited the BHS model of the North Polar Spur and related galactic structures based on the 408-MHz radio continuum and ROSAT all-sky soft X-ray data. We have shown that the NPS and its western and southern counter-spurs draw a giant dumbbell-shape on the sky necked at the galactic plane. The morphology and soft X-ray intensities of the spurs can be interpreted as due to a shock front originating from a starburst at the Galactic Center some 15 million years ago with a total energy of the order of $\sim 10^{56}$ ergs or 10^5 type II supernovae.

We have simulated radio continuum and soft X-ray skies based on the BHS galactic center starburst model. Simulated all-sky distributions of radio continuum intensities can well reproduce the radio NPS and related spurs, as well as many other radio spurs in the tangential directions of spiral arms. Simulated soft X-ray maps in 0.75 and 1.5 keV bands can reproduce the ROSAT X-ray NPS, its western and southern counter-spurs, as well as the absorption layer along the galactic plane. The observed R12 band polar-cap

features are also well reproduced in our model.

If the present BHS model for the spurs is correct, we may be able to use the ROSAT all-sky maps to probe the gas dynamics in the halo-intergalactic interface. We may also be able to directly date and measure the energy of a recent Galactic Center starburst in the Milky Way, which can also be compared with similar BHS phenomena in nearby starburst galaxies.

Acknowledgement: The author would like to thank the ROSAT experiment staff for making the FITS formatted data of the X-ray survey available via an internet link to "SkyView" operated by NASA. The author is indebted to the anonymous referee for the invaluable comments and suggestions, with which the paper has been very much improved.

References

Berkhuijsen, E., Haslam, C. and Salter, C. 1971 AA 14, 252.

Cecil, G. 1999 NAOA Preprint No. 850 (in "Imaging the Universe in Three Dimensions", eds. W. van Breugel and J. Bland-Hauthorn, ASP Conf. Series).

Duric, N., Seaquist, E.R., Crane, P.C., Bignell, R.C., Davis, L.E., 1983, Ap.J.L, 273, L11.

Egger, R. J., and Aschenbach, B. 1995 AA 294, L25.

Egger, R. 1993, Ph. D. Thesis, Univ. Munich, MPE Report No. 249.

Genzel, R., Eckart, A., Ott, T., and Eisenhauer, F. 1997, MNRAS 291, 219.

Ghez, A., Morris, M., Klein, B. L., Becklin,E.E. 1998, ApJ 509, 678.

Haslam, C.G.T., Salter, C.J., Stoffel, H., Wilson, W.E., 1982, AA Suppl. 47, 1.

Hartmann, D. and Burton, W.B. 1997, in Atlas of galactic neutral hydrogen, Cambridge University Press, Cambridge.

Heckman, T. M., Armus, L., Miley, G. K., 1990, ApJS 74, 833.

Laumbach, D. D., and Probstein, R. F. 1969 J. Fluid Mecha. 35, 53.

McCammon, D. and Sanders, 1990, ARAA 28, 657.

McCammon, D., Burrows, D.N., Sanders.W. T., and Kraushaar, W. L. 1983, Ap.J. 269, 107.

Möllenhoff, C. 1976 AA 50, 105.

Morrison, R. and McCammon D. 1983 ApJ 270, 119.

Nakai, N. 1992, PASJ 44, L27.

Nakai, N., M.Hayashi, Handa, T., Sofue, Y., Hasegawa, T., and Sasaki, M. PASJ 39, 685, 1987.

Oort, J.H. 1977 ARAA 15, 259.

Pietsch, W., Trinchieri, G., and Vogler, A 1998 AA 340, 351.

Pietsch, W., Vogler, A., Klein, U. and Zinnecker, H. 1999 AA in press.

Ryter, Ch. E. 1996 ApSpSc 236, 285.

Sakashita, S. 1971 ApSpSc 14, 431.

Snowden, S. L., Egger, R., Freyberg, M. J., McCammon, D.,Plucinsky, P. P., Sanders, W. T., Schmitt, J. H. M. M., Trümpler, J., Voges, W. H. 1997 ApJ. 485, 125

Sofue, Y. 1976, AA 48, 1.

Sofue, Y. 1977, AA 60, 327.

Sofue, Y. 1984, PASJ 36, 539.

Sofue, Y. 1993, PASP, 105, 308.

Sofue, Y. 1994, ApJ.L., 431, L91

Sofue, Y. and Reich, W. 1979 AAS 38, 251

Tomisaka, K. and Ikeuchi, S. 1988 ApJ 330 695

Uchida, Y., Shibata, K., and Sofue, Y. 1985 Nature 317, 699

van Albada, G.D. and van der Hulst, J.M., 1982 AA 115, 263.

Vogler, A., and Pietsch, W., 1999a AA 342, 101.

Vogler, A., and Pietsch, W., 1999b AA in press.

Fig. Captions

Fig. 1: (a) Top: Enhanced view of galactic spurs in the 408-MHz radio continuum, as obtained by applying a relieving method to the Bonn-Parkes all-sky survey in the galactic coordinates (Haslam et al 1982). Major features discussed in the text are indicated by arrows. The Galactic Center is at the map center, and the longitude increases toward the left with the both side edges being at $l = 180°$. The Galactic North Pole is to the top, and South Pole at the bottom.

(b) Middle: An X-ray all-sky image in the R45 (0.75 keV) band as reproduced from the ROSAT survey (Snowden et al 1997).

(c) Bottom: Schematic overlay of the bipolar hyper shell (BHS) on the ROSAT 0.75 keV map.

Fig. 2: 408 MHz radio map in a $\pm 50\circ$ square region around the Galactic Center. A relieving method has been applied in the direction of longitude (left panel) and radial direction (right panel). Symmetric sets of spurs emerging from $l \sim 20°$ and $\sim 340°$ are recognized, which labeled as NPS, NPS-West, SPS and SPS-West (see the text).

Fig. 3: Enhanced radio (left) and X-ray (right) images of the North Polar Spur. Displayed area is $\pm 50°$ square centered at $(l, b) = (0, 30°)$.

Fig. 4: (a) Calculated shock front in the galactic halo at 1 and 2×10^7 yr after an explosion and/or a starburst at the nucleus with a total energy of 3×10^{56} erg (Sofue 1984).

(b) Same as (a) but showing the shock front every 2 Myr.

(c) Schematic view of a bipolar conical shock front for a case of lower gas density in the upper halo and intergalactic space.

Fig. 5: Simulated all-sky radio intensity distribution in the galactic coordinates according to the bipolar hyper shell model. Intensity scales are relative, and absolute values are arbitrary.

(a) Hyper shells with a flat galactic disk and a thick disk without spiral arms.

(b) Hyper shells with a galactic disk comprising logarithmic spiral arms and a thick disk.

(c) Observed 408 MHz all-sky map in gray scale (Haslam et al 1982). Thick arrows indicate the bipolar hyper shell. Thin arrows indicate the tangential directions of the local and inner spiral arms, where radio spurs are emerging from the disk toward the halo.

Fig. 6: Logarithmic spiral arms with pitch angle of $6°$ and condensation of about 5 times the averaged value.

Fig. 7: Simulated all-sky distributions in the R45 (0.75 keV) X-ray bands.

(a) Intrinsic intensities of the hyper shells and disk without interstellar extinction.

(b) Intensity distribution for an exponential hydrogen absorbing layer, but without spiral arms.

(c) Same as (b) but for a parabolic conical cylinders. The Ω shape of the North Polar Spur is better reproduced by the hyper shell model of (b)

Fig. 8: Simulated all-sky X-ray views in R12, R45 and R67 bands (left) compared with the corresponding ROSAT sky views (right). The absorbing hydrogen layer is assumed to comprise logarithmic spiral arms as in Fig. 6. The polar caps in 0.25 keV band, dumbbell-shaped morphology in 0.75 and 1.5 keV bands with the absorption features along the galactic plane are well reproduced by the BHS model calculations